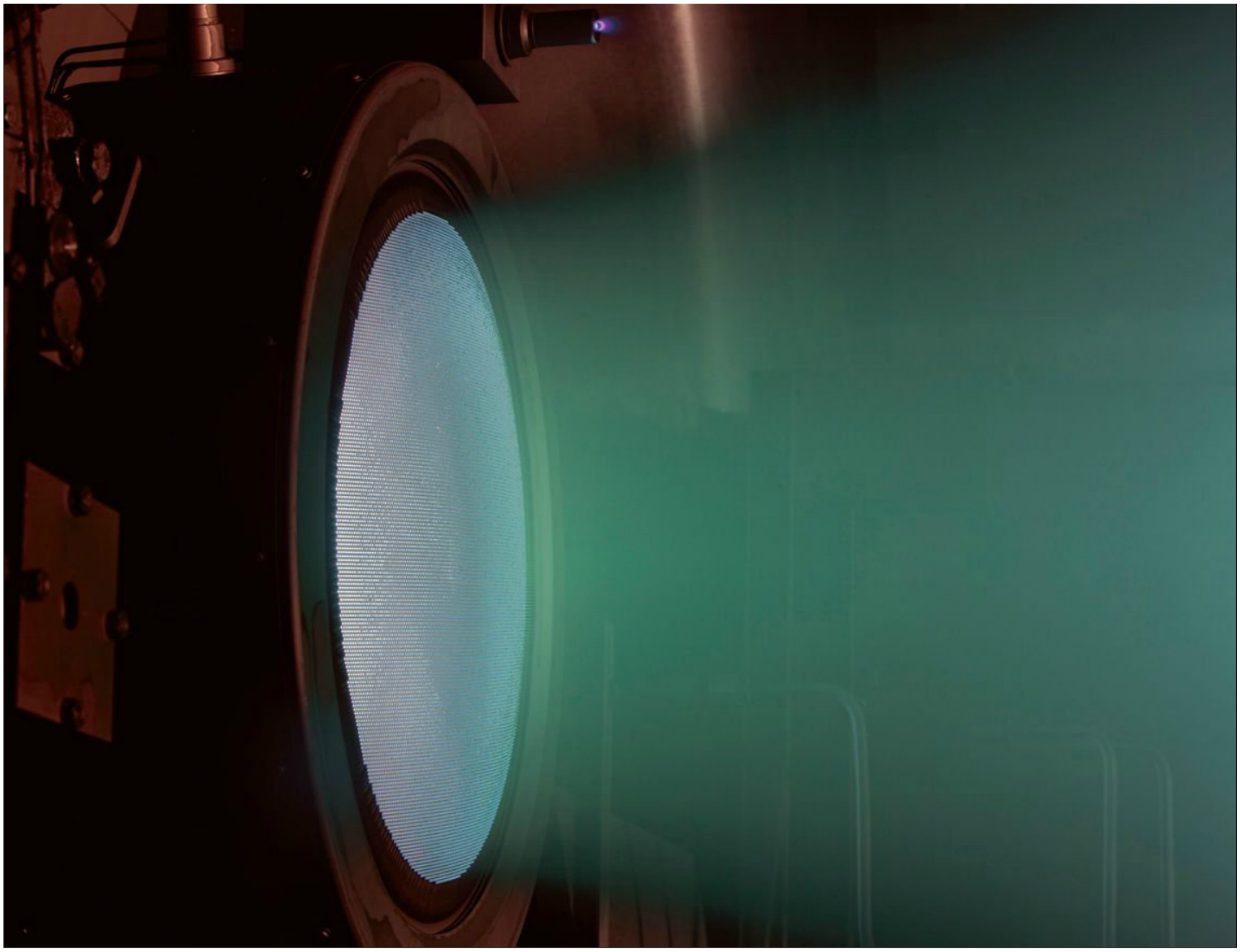


NASA's Evolutionary Xenon Thruster (NEXT) project has developed a 7-kW ion thruster that can provide the capabilities needed in the future.

Solar electric propulsion (SEP) is a general term for a variety of systems that use solar energy to generate electricity that then is combined with a gas to provide in-space propulsion. While often perceived as a late 20th century technology, it actually was first proposed in 1906 by American rocket pioneer Robert Goddard, who conducted the first experiments with ion thrusters a decade later at Clark University, a private research university in Worcester, Massachusetts.

The most widely known form of SEP is ion propulsion (IP), perhaps most familiar to the public from the original *Star Trek* TV series and *Star Wars* films. In the former, it was described as a super-fast alien propulsion system that the starship Enterprise could not catch; in the latter, it was used by Imperial TIE (twin ion engine) fighters. While sounding exotic and fast, neither fictional representation was correct.

by J.R. Wilson
Contributing writer

History and progress

From studies beginning in the 1950s, the former Soviet Union developed two versions of SEP, known as Hall thrusters—wide acceleration zone or stationary plasma thrusters (SPT) and narrow acceleration zone or TAL (thruster with anode layer). The USSR's Meteor, launched in December 1971, was the first spacecraft to use SPT in space. Since then, more than 200 Hall thrusters have flown on Soviet and Russian spacecraft, primarily for satellite stabilization, without a single failure in orbit.

"Fundamentally, SEP is a very efficient method for doing in-state propulsion. The tradeoff for that is lower thrust," notes John Abrams, systems engineering program manager at Analytical Mechanics Associates. "It's a natural evolution to use SEP for things like LEO-to-GEO transfer, which really is a commercial business lane in that it ultimately can put those craft on a smaller launch vehicle to reduce costs. There also are a number of things that can be done once you are in orbit—orbit raising, stationkeeping, inclination change, making up for atmospheric drag.

Harnessing the power of the Sun to provide thrust for transport in space has long been a part of science fiction imagery. Now a reality after decades of development, it has found increasing use for applications ranging from station-keeping to orbit-raising. Obstacles remain, but evolving technology should enable expanding applications of this weight-saving form of energy, possibly even for manned spaceflight.

New thrust for solar electric propulsion

"SEP has been around for awhile, and the core technology is fairly well known. The problem is when it is scaled up, and the unknown risks that may occur. There also are known issues, including high-power-level processing, increasing efficiency within that power processing, the development and deployment of very large solar arrays, increasing the voltage of the arrays and of the system as a whole."

AMA was one of five companies—along with Boeing, Lockheed Martin, Ball Aerospace, and Northrop Grumman—contracted by NASA in 2011 to develop a mission concept demonstrating SEP technologies and capabilities, and the infrastructure required to affordably sustain a human presence in space. That study contract came after some 20 years of U.S. focus on SEP.

In 1992, specialists from JPL, NASA Glenn, and the Air Force Research Lab, supported by the Ballistic Missile Defense Organization (now the Missile Defense Agency), visited Soviet labs to evaluate a 100-mm-diam SPT-100 thruster. In the two decades since, Hall thrusters have flown on a variety of U.S. and European spacecraft in LEO and GEO orbit.

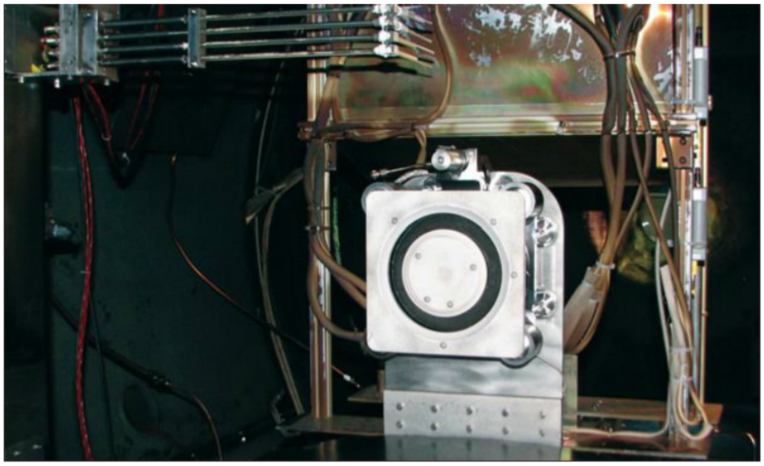
In 2003, ESA became the first organization to use Hall thrusters in lunar orbit, for the SMART-1 mission.

Recent efforts

The first operational flight of a U.S.-made Hall thruster did not come until 2010, using an Aerojet BPT-4000 on the military's Advanced Extremely High Frequency GEO communications satellite. The BPT-4000 produces 4.5 kW of power, the highest on any Hall thruster ever flown in space, giving the satellite orbit-raising capability and enabling it to perform standard station-keeping tasks as well.

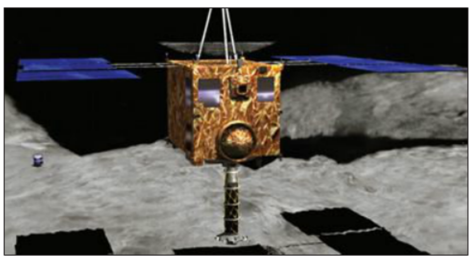
While both types are electrostatic ion thrusters, Hall thrusters differ from IP en-

Various Soviet and Russian SPT Hall thrusters have been developed over the years.



An Aerojet BPT-4000 is in use on the Advanced Extremely High Frequency satellite.

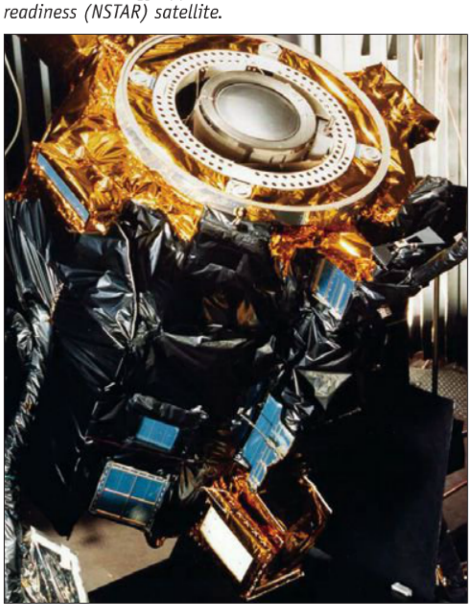
gines in how and where the electron plasma and magnetic fields interact with charged ions to produce thrust. IP uses layered grids rather than the cylindrical tube of the Hall. Both typically use xenon gas, which has no charge and is ionized by bombarding it with energetic electrons.



Japan's Hayabusa was launched in May 2003 and rendezvoused with the asteroid Itokawa in mid-September 2005.

"Hall generally have a higher thrust-to-power. If you want a rapid orbit change, then Hall thrusters are good; if you want to maximize payload and reduce propellant mass, the ion thrusters are better," says Michael Patterson, senior in-space propulsion technologist with the NASA Engineering Directorate's Space Propulsion Branch. "So there are niches for all the different technologies, depending on mission demands. And some have more than one on the same spacecraft."

Ion propulsion was tested on the SEP technology application readiness (NSTAR) satellite.



The most common way to generate electricity in space is with photovoltaic panels. The most widespread application of SEP has been on commercial GEO communications satellites (comsats), which already have large solar arrays on board.

"Ion and Hall thrusters are specific technologies that can be implemented to do that, along with the arcjet—one of the first used for GEO comsats," says NASA aerospace engineer David Manzella. "Several more are under development, including variable specific impulse magnetoplasma, dynamic pulsed plasma, etc.—a whole family of different techniques to implement SEP."

NASA made the first use of IP in space in 1964 aboard the SERT-1 (space electric rocket test-1) mission, demonstrating that it could perform successfully in space. Since then, IP has been tested on the 2.3-kW NASA SEP technology application readiness (NSTAR), the 6.9-kW NASA evolutionary xenon thruster (NEXT), the nuclear electric xenon ion system (NEXIS), the 25-kW HiPEP (high power electric propulsion) ground test, the EADS radio frequency ion thruster (RIT), and the DS4G (dual-stage 4-grid) system.

"There are emerging devices at higher power levels, such as the 7-kW NEXT," says Manzella. "They are growing in power because the need is increasing. There are evolutionary developments—larger, more efficient, higher power devices—along with much less mature alternate ideas that may offer advantages over the current state of the art.

"At the 5-kW and 10-kW level, in addition to station-keeping, they also are using them for a portion of the orbit transfer on GEO comsats, in combination with traditional fueled thrusters. Because they are low thrust, using SEP could take up to a year to get the satellite into the desired orbit. During the initial one-month checkout period, for example, they may use SEP to move the satellite, then complete it—maybe 75%—quickly with chemical thrusters."

NSTAR was the first successful demonstration of ion propulsion in interplanetary space, carried aboard NASA's Deep Space 1, launched in 1998.

In 2003, the Japanese space agency used four xenon ion engines on its Hayabusa mission to rendezvous with an asteroid, collect samples, and successfully return to Earth. Although the engines developed technical problems, an in-flight reconfiguration allowed one of the four to be repaired and complete the journey home.

The big drawbacks

In 2007, NASA used three heritage Deep Space 1 IPs on its Dawn mission to explore the asteroid Vesta and dwarf planet Ceres, firing one engine at a time to take the spacecraft on a long outward spiral to its targets. Firing continuously for four days, Dawn's ion drive is capable of accelerating from 9 to 60 mph in that period.

That, in fact, illustrates the biggest problem with SEP—and the inaccuracy of the science fiction depictions of ion propulsion: It provides an extremely low-power thrust compared to chemical engines, only slowly building speed for the full duration of an interplanetary mission. Also, because it is based on electricity generated by sunlight, the farther the spacecraft gets from the Sun, the less power a SEP engine is capable of generating.

"IP engines arguably are the most advanced form in terms of efficiency—specific impulse capability—but also the most complicated," notes Patterson, who was principal investigator for NEXT at NASA. "NEXT is under development through the Science Mission Directorate. We don't yet have a mission for it, although [NASA] Glenn has declared us Technology Level 6, which means we are ready for flight.

"As we speak, I'm running the prototype thruster at Aerospace Corporation to characterize the engine so we can understand the interfaces required to integrate it onto a spacecraft. We're advocating for its application on NASA and other non-NASA government and commercial missions, because it is a very capable technology. The engine just passed a throughput of 7.5 kW, which means we could have flown Dawn with one NEXT thruster."

In February 2012, NASA awarded a contract to Northrop Grumman to develop a system capable of creating 300 kW of electrical power.

"There has been a lot of work done on developing various types of thrusters, so we have focused on power generation. And the system we have developed can work with many of those thrusters, which are suitable for various missions," notes Amy Lon, Northrop Grumman SEP lead systems engineer.

"There are not a lot of issues facing low-power SEP—it's in a lot of satellites and is now a production line item. But when you get to hundreds of kilowatts for high-power SEP, there still are a lot of issues in generating and transporting that power to the thrusters."

Perhaps the one problem technology cannot solve, she adds, is distance: "If you are going to Jupiter and beyond, where solar intensity decreases, the question is what to use for your power source. In the past, nuclear has been the only reliable source for targets that far away. So Jupiter is kind of the limit for SEP."

Three heritage Deep Space 1 ion propulsion engines were used to power the Dawn spacecraft.

Generating power

For missions within the inner solar system, however, the company's use of a solar panel and Brayton engine combination that does not require football field-size solar arrays has major advantages, according to Ron Polidan, director of Northrop Grumman Science and Weather Systems.

"We are still talking to NASA Glenn and continuing to advance what we call our solar dynamics approach to power generation," he says. "NASA's Dawn is the first to use SEP as prime propulsion. If you look at NASA's use for deep space missions, because SEP works as a steady thrust, it greatly relaxes the launch window.

"I now can adjust my thrust to compensate for changes in the actual launch time. That really helps when you have to go from the Earth to some other spot where alignment is vital. SEP gives you a much easier way to compensate for the vagaries of launching."

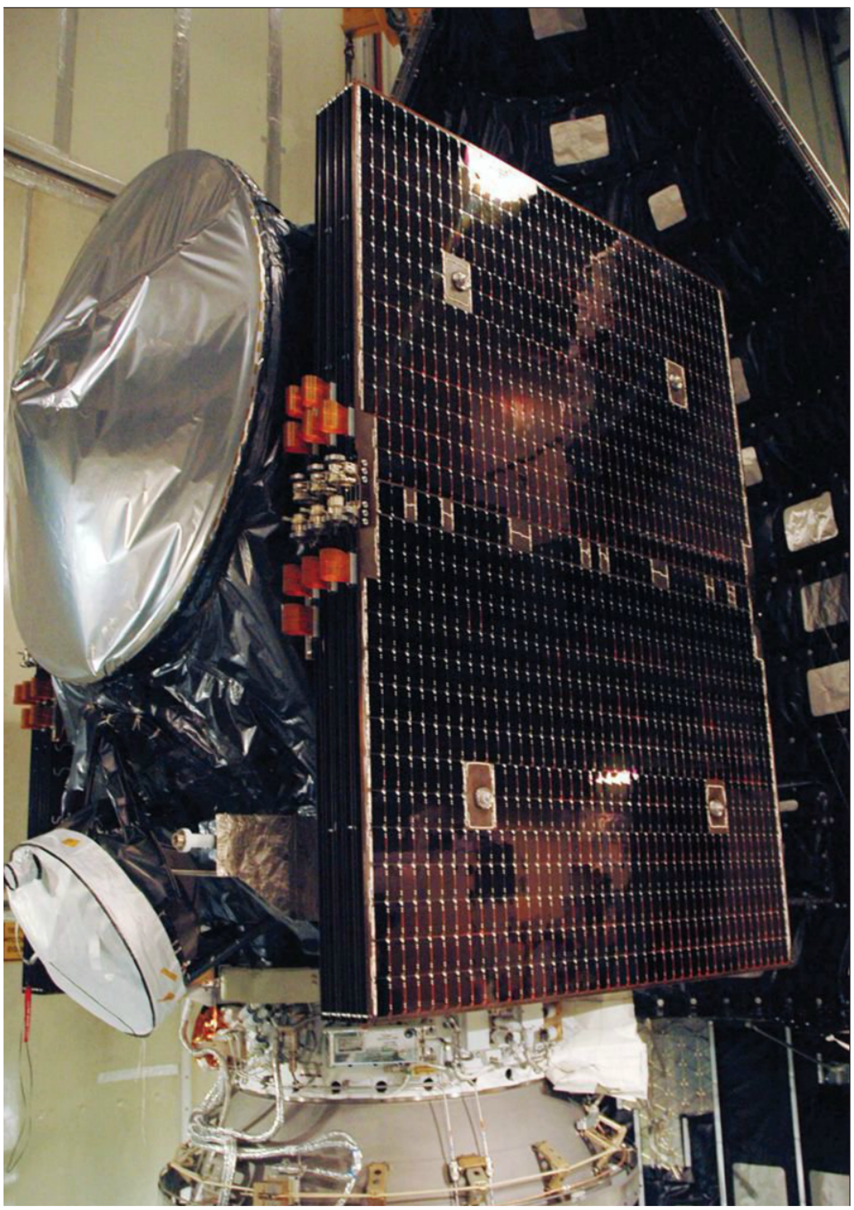
Manned flight and other possibilities

Although Lon appears to be in a minority for now, she also sees a future for SEP in manned spaceflight.

"That's one of the foundational missions NASA has defined for SEP. One of the two architectures they have been looking at for many years is to use SEP as a tug to take astronauts from near-Earth to GEO, while the other would take astronauts from near-Earth space to Mars," she says. "For an equivalent amount of chemical propulsion to get astronauts from Earth, you would have to carry a lot of fuel, which raises issues of getting all that together into space.

"Even though SEP only provides a couple of tenths of Newtons, it is continuous—you add a little every second, so you are looking at the total acceleration you can get out of the system. The initial ramp-up to achieve the velocity you need may be slower, but eventually you get there."

Dawn's solar array wings are folded to fit inside the nose section of protective fairing before launch. The solar arrays are used in tandem with the SEP.



Polidan believes that NASA has taken the lead in SEP, but points out that interest in it has increased throughout the world. He also sees somewhat greater advancement in civil applications of SEP than in defense applications.

"Dawn has proved it is a reliable propulsion source, and I would not be surprised to see future NASA missions using ion," he says. "We're working on our own exoplanetary mission—Starshade—and are seeking business from our other science customers. We also talk to a lot of people in academia, and a fraction of those are looking at SEP elements or missions that alleviate a lot of the problems they would have with chemical."

AMA's Abrams agrees: "In my opinion, it is less about the technologies and more about the engineering. The core technologies are there, you just need to scale the systems up to larger power levels.

"I think by the end of this decade it will be used more for commercial markets, to put GEO satellites in orbit. But I'm hoping it will be used as a methodology for human exploration in the 2020s. In the 2030s and beyond, we may go away from SEP and on to nuclear-based systems. It's still electric, just the power process is different, nuclear instead of solar—NEP."

Northrop Grumman SEP program manager James Munger says one advantage to his company's approach is the direct creation of AC power. By contrast, typical photovoltaic designs generate DC current that must then be converted to AC.

"AC power is easier to transmit, and we can optimize our power generation to the particular needs of the thruster at the time," Munger explains. "The interesting thing," he continues, is that "by generating AC… we not only do not use photovoltaics, which have trouble getting large to enough to service some of the larger payloads, [but] we also can get the power out to the thrusters without using difficult electronics to convert DC power back to something the thrusters can use."

Ball Aerospace also had a different perspective during the NASA study, that of end user on their satellites rather than the builder of thruster systems or solar arrays.

"We have looked at a lot of applications, both near Earth and deep space. We want to keep our hand in with everyone developing this technology," says aerospace engineer William Deininger, Ball's principal investigator on the NASA SEP study. "For the current applications we foresee, existing technology is largely ready to fly.

"It would be nice to have thrusters at higher powers, but it depends on whether you want to increase mass, decrease time, or do both. There are cases where you can fly to a planet using chemical in 10-15 years, while SEP can reduce that roughly by half or, with the same flight time, have a larger payload."

One area where things still need to be done is lightweight solar arrays, he says, which probably are the last item to be ticked off to get into the 20-50-kW range.

"The Human Exploration Directorate at NASA are the folks proposing a 300-kW-plus thruster, which is required to deliver payloads to support missions," Deininger says. "You wouldn't use it for humans, but for habitats, fuel, food, etc. When we did studies, that was the original intent, to develop a near-term solution to taking risk out of the higher power applications and make it scalable to a 200-300-kW class."

Future outlook

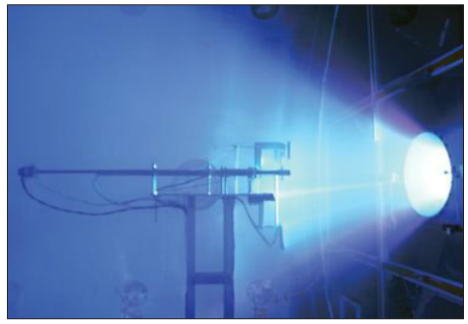
Deininger sees use of the various forms of SEP expanding through the coming decades, especially as continued R&D improves efficiencies and thrust.

"In this decade, we launched Dawn. In the next 10-20 years, I think you will see NASA's NEXT thruster applied to higher energy missions, which the thruster on Dawn couldn't [provide]. So I think some missions will select SEP for high energy needs," Deininger says.

"Hall will be used more in near-Earth [missions], where you want higher thrust to get there quickly and save on fuel requirements. We're trying to understand those, as a company, and see what we can do to help out with it. Our expectation is that these missions will be competed, and we can team with thruster partners in making those bids."

One of those new systems in development is the French highly efficient multistage plasma (HEMP) ion thruster.

"HEMP is based on traveling wave tube technology; they have brought it to a pretty good state of development in a relatively short time. Between it, ion, arc, and Hall, I think you have the main SEPs for near-term. Further out, you will have the MPD [magnetoplasmadynamic] thruster and VASIMR [variable specific impulse magnetoplasma rocket]. Those two might come to fruition in the future when systems that provide higher power are available in orbit," Deininger says, but adds that he still does not see it being used for manned missions.



In 2009, Ad Astra Rocket performed tests on the VX-200 prototype with 2 tesla superconducting magnets. They expanded the power range of the VASIMR up to 200 kW.

"Because SEP uses electrical energy to generate thrust, it is really low thrust; you want to get human crews to their destination quickly to reduce exposure to radiation. If we have megawatt thrusters that can move quickly, it might. But the most likely use is prepositioning supplies with SEP and getting humans there using chemical [engines]. You can get more mass to the Moon or Mars with a SEP system, but you can't get there fast enough for human transport."

NASA, however, is still looking at the possibility of growing the power of SEP thrusters or using their continuous acceleration capability, without the increased mass of chemical engines, for interplanetary missions later in this century.

"NASA has been developing architectures for human exploration beyond LEO; in those studies, there have been several mission concepts using very high-power SEP vehicles in a supporting role," Manzella says. "Those would be multi-hundreds of kilowatts, more than an order of magnitude greater in size and power than systems flying today.

"In fact, they would have solar arrays equal in area to those on the international space station. Because those systems are so large, it is not anticipated we would directly develop something of that size, but more intermediate-size spacecraft that would serve as stepping stones."

The nearer term

NASA has efforts under way to define what a reasonable intermediate application might be, with what Manzella says is an agreement the nominal thruster would be on the order of 30 kW. To that end, the agency is investing in the development of advanced solar arrays and systems with higher power and performance that could use them.

"That is based on the future mission pull for human exploration objectives, which are still being developed—and those could change," he adds. "But in the midterm, having 30 kW flying by the end of the decade as a precursor to multi-hundred-kilowatt systems that would fly in the following decade.

"Because some NASA science missions are deep space, there are possibilities those might be well served by SEP, but NASA generally competes those missions, based on the science proposed. There is a regular schedule within planetary sciences, for example, for discovery, and some of the proposals they receive involve SEP. There also may be international missions that could use SEP, both science and commercial."

The use of SEP for LEO and GEO station-keeping has been satisfied for decades by low-thrust engines, while the demands of interplanetary robotic probes have demonstrated how relatively minor improvements in power can both supplement and, in some cases, even replace chemical engines. But as humans eventually return to the Moon, then move on to Mars and other interplanetary destinations, the enabling technologies that have gotten SEP to its current level will be replaced by new and more demanding developments.

"We are looking at an ion engine capability of scaling to a very high power. A downside to NEXT is that their 'conventional' design doesn't freely allow scaling to high power at specific impulse. You can build big ion engines with high power; what you want is to scale ion engines to very high power, but modest specific impulse of exhaust velocities," says Patterson.

"We call it the next-generation electric propulsion thruster, really a family of engines whose design basis is the annular geometry ion engine—going from a cylindrical shape to annular, which allows you to scale the engine. Other advantages include being able to stick another engine, like a Hall, in the middle of that and run one [engine] during parts of the mission, the other on the rest, whichever fits best. Or you can nest multiple engines, which offers simplification of manufacturing and reduced cost—four nested annular engines could accommodate a range of missions.